

THE KILOMETRIC JOVIAN RADIO SOURCES AT THE IO TORUS

Yolande Leblanc

*Observatoire de Paris
92195 Meudon, France*

Abstract

The Jovian kilometric radiation (KOM) was discovered during the flyby of Jupiter by Voyager (V) 1 and 2. Two experiments detected this radio emission, the Planetary Radio Astronomy (PRA) and the Plasma Wave (PWS) instruments. The statistical analysis of KOM led to the determination of the average density spectrum, the polarization sense of the incoming waves and the beaming of these emissions. The narrow band emission source of KOM (nKOM) does not rotate with a single period, the dominant regions being System III and about 3% corotation lag (System IV). When selecting nKOM episodes within one day of alignment of the probability peaks in System III and System IV, the probability of detecting nKOM is strongly enhanced and therefore exhibits a period of 14 days. Recent studies show that the beaming could result from the emission mechanism, and that bKOM and nKOM would be produced by the same conversion process operating at the magnetic equator, on the outer flanks of the Io torus, within $\sim 2^\circ$ for the bKOM sources and at latitudes $\geq 8^\circ$ for nKOM sources. Many consequences on the torus characteristics are derived, taking advantage from different observational configurations. In particular the beaming results indicate that, on the nightside, the torus is farther and has a smaller density gradient than on the dayside. A remote sensing technique has been used to compute the torus density profiles from the observed KOM beaming, when no in-situ observations are available.

Introduction

One of the many discoveries made by Voyager 1 and 2 was the detection of intense Jovian radio emission at kilometric wavelengths (KOM) by the Planetary Radio Astronomy (PRA, Warwick et al., 1977) and Plasma Wave instruments (PWS). The frequency spectrum of KOM has been observed to extend from frequencies as low as 1 kHz to as high as 1.4 MHz. Three components were distinguished in that range: a broadband sporadic emission, or bKOM (Warwick et al., 1979a,b; Desch and Kaiser, 1980; Leblanc and Daigne, 1985a,b), a smooth narrow-band emission, or nKOM (Kaiser and Desch, 1980; Daigne and Leblanc, 1986), and a non-thermal trapped continuum within the magnetosphere (Scarf et al., 1979; Kurth et al., 1979, 1980b; Leblanc et al., 1986; Kurth et al., 1986b).

In this paper we concentrate on bKOM and nKOM emissions, the general properties of these emissions being reviewed with emphasis on the similarities and differences. The inferred properties are then developed, in particular the beaming, the source locations, the emission mode, and mechanism. It will be shown that these radio sources are at the

Io torus: many consequences on the torus characteristics will be outlined, in particular the Io torus fluctuations are discussed.

1. Observed properties

1.1 Average flux density spectrum of the magnetized planets

Figure 1 shows the average observed flux density spectrum of the four magnetized planets in the kilometric wavelength range (Gulkis and Carr, 1987). Jupiter is the most powerful transmitter, and the shape of its density spectrum curve is totally different from the three others. This can be easily understood since we know that the radio sources of the Earth, Saturn and Uranus are believed to be located in the polar regions. Instead, the Jovian kilometric radio sources are believed to be located at the Io torus and their contribution to the average spectrum is very important in the kilometric range.

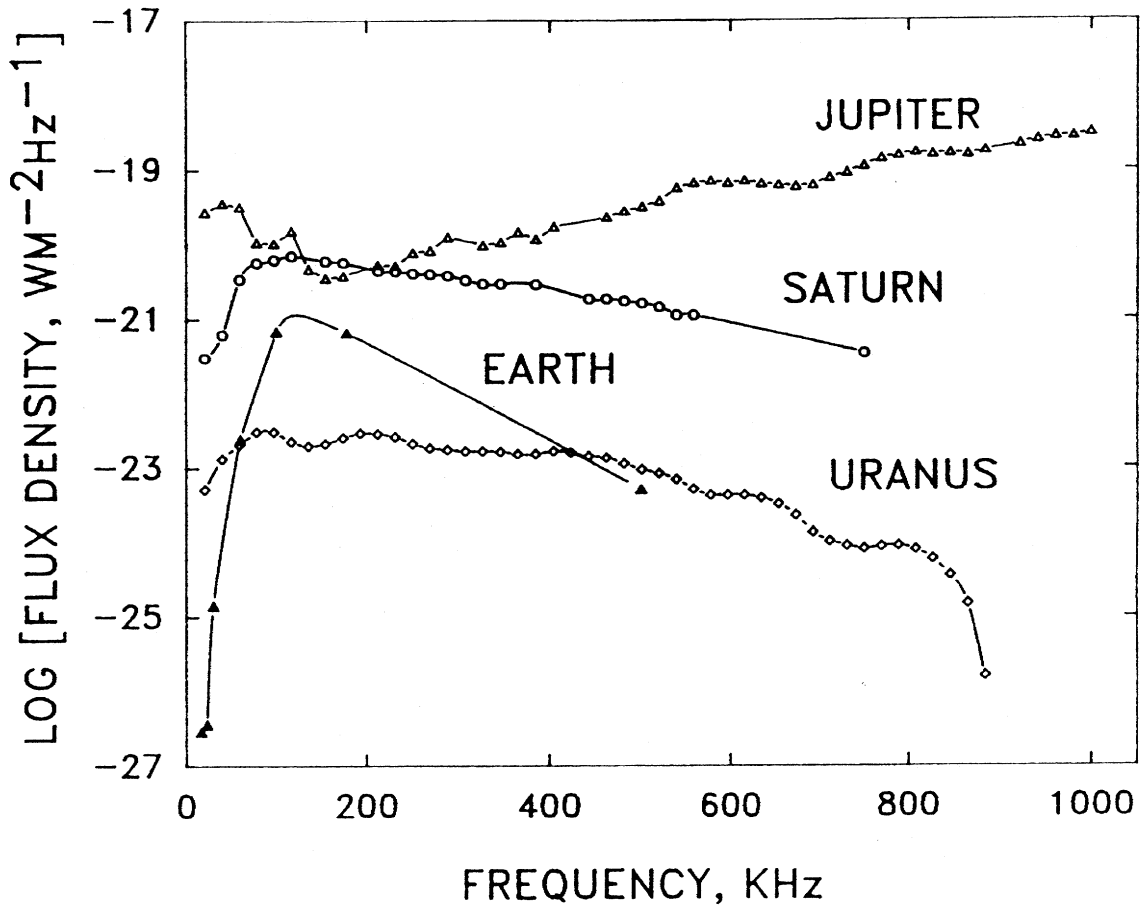


Fig. 1: Low frequency radio power spectra of Earth, Jupiter, Saturn and Uranus (after Gulkis and Carr, 1987). The curves are for peak values of the flux densities, which have been adjusted to the distance 4 AU.

1.2 Observer's local time and Jovicentric latitude

The observations made by Voyager (V1 and V2) PRA experiments during 850 Jovian rotations from January 1, 1979 to December 31, 1979 have been analyzed. This period includes the pre- and post-encounters for V1 and V2 at distances from -2180 Jovian radii (R_J) through $+3215 R_J$, respectively. The pre-encounter observations were made at 10:30 local time and 3.2° Jovicentric latitude for V1, and 9:30 local time and 7.5° Jovicentric latitude for V2. The post-encounter observations correspond to 4:15 local time and 5.3° for V1, and 3:00 local time and 5.7° for V2 (see Figure 1 of Alexander et al., 1981). We have taken advantage of these different observational configurations to determine the beaming and the source locations.

1.3 Occurrence probability in CML (Central Meridian Longitude)

- bKOM emission: Comparison of the occurrence probabilities of V1 and V2 pre- and post-encounters for the same distance range are given in Table 1 (the values are deduced from Figures 3 and 4 of Leblanc and Daigne, 1985a). For V1, the peak value is higher for night-side observations when the spacecraft (s/c) declination was higher. The comparison of V2 pre- and post-encounter shows that it is higher for dayside observations, when the V2 declination was higher. On the other hand, the histograms of V1 and V2 post-encounters are very similar within the same distance range up to $1000 R_J$. From the comparison of these histograms, together with the V2 pre-encounter, we conclude that the peak value of the occurrence diagram is mostly dependent on the zenographic latitude of the observer and does not depend on the local time of the observations. On the dayside hemisphere the maximum occurrence is in the range $150^\circ - 240^\circ$ CML and very few emissions were observed outside of the main peak (Figure 2a). The areas of V1 and V2 histograms are also representative of the bKOM absolute occurrence probability since they refer to the same distance range. The area of the V2 histogram is twice the area of the V1 histogram, which confirms the latitude effect of the observer on bKOM occurrence probability. On the nightside hemisphere (Figure 3a), there are two peaks in the occurrence probability, the first one at 140° CML and the second one at about 250° CML. Outside the main peaks, there is a rather important activity level within the ranges $0^\circ - 90^\circ$ and $300^\circ - 360^\circ$ CML. This latter emission is mainly observed on the nightside hemisphere.

Table 1: Occurrence probability of bKOM

Spacecraft	Local Time	s/c Declination	Peak Value
V1	10:30	$3^\circ 2'$	0.55
V1	04:15	$5^\circ 2'$	0.70
V2	03:00	$5^\circ 7'$	0.70
V2	09:30	$7^\circ 5'$	0.90

DAYSIDE OBSERVATIONS

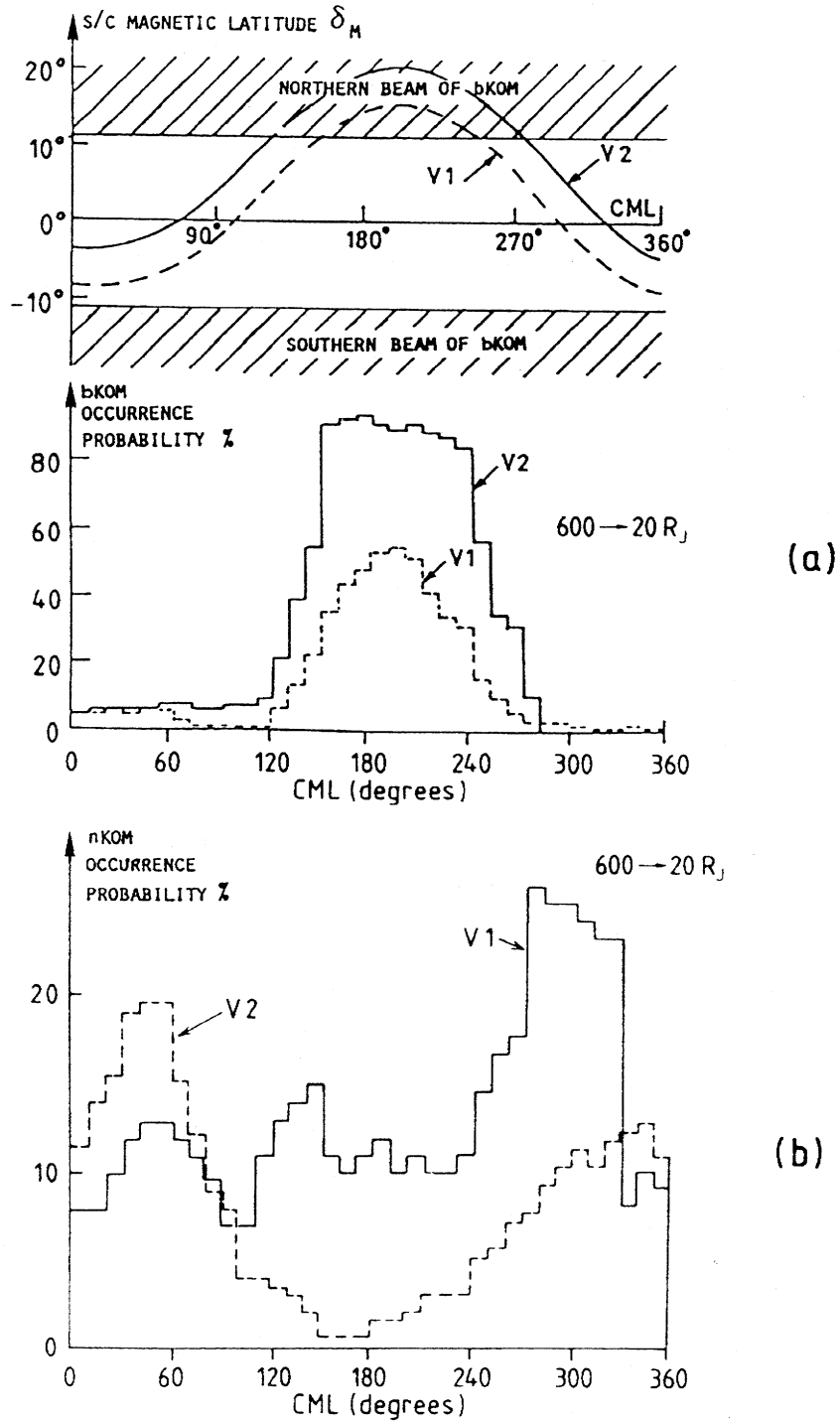


Fig. 2: Occurrence probability of (a) bKOM and (b) nKOM for dayside observations (pre-encounter). At the top, the spacecraft magnetic latitude during one Jovian rotation with the indication of the lowest boundary of bKOM beam, $\sim 11^\circ$, as deduced from the occurrence probability.

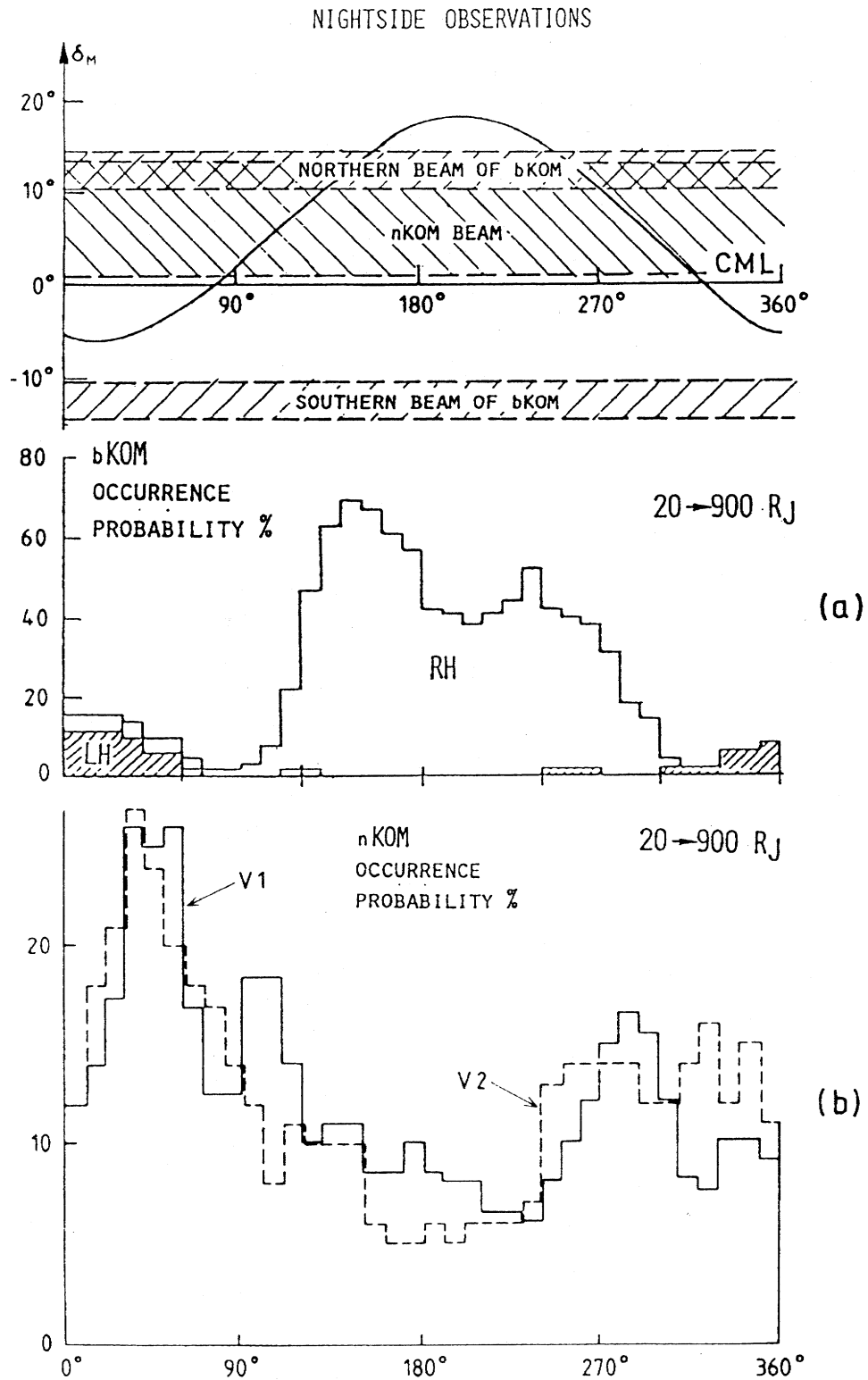


Fig. 3: Occurrence probability of (a) **bKOM** and (b) **nKOM** for nightside observations (post-encounter). The boundaries of **bKOM** beam are 11° and 14° : the beam is swept twice by the observer (**V1** or **V2**) at each Jovian rotation. The boundaries of **nKOM** beam are 2° and 12° .

- nKOM emission: Before encounters, nKOM and bKOM emissions appear unpolarized due to the antenna electric plane position with respect to the source direction. Therefore nKOM emissions, less intense than bKOM, are not always identified in the CML range of $90^\circ - 300^\circ$, which would explain the fewer emissions in that range. However, the identification of nKOM in the other CML ranges where bKOM usually does not occur, is quite reliable. If we consider V1 and V2 observations, two peaks of occurrence are observed, one at $\sim 40^\circ$ CML and the other at $\sim 300^\circ$ CML (System III).

After encounters, nKOM is more easily distinguished from bKOM since both emissions are polarized in the opposite sense when occurring in the same CML range. One large peak occurs at $\text{CML} = 40^\circ$ (System III) for V1 and V2 observations (Figure 3b). Since the two spacecraft were at the same latitude and at similar local time, the observed distribution is certainly significant, the two periods of observations being quite distinct.

1.4 Polarization

Ortega-Molina and Daigne (1984) and Leblanc and Daigne (1985a,b) established that the electric plane of the PRA antenna system was different from the plane of the monopoles, so that the circular polarization does not reverse at 90° (angle between the source direction and the normal to the antenna plane) but at a value of $\sim 70^\circ$. As a result there is no polarization reversal of bKOM from dayside to nightside observations, as was claimed by Desch and Kaiser (1980) or Alexander et al. (1981). When the spacecraft were in the northern magnetic hemisphere, the emission was seen right-hand (RH) polarized, and seen left-handed (LH) when the s/c were in the southern hemisphere.

Daigne and Leblanc (1986) have shown nKOM polarization in terms of CML for V1 and V2 observations: the emission was seen right-handed in the range $0^\circ - 90^\circ$ and $300^\circ - 360^\circ$ CML, when the spacecraft were in the southern hemisphere, and left-handed in the range $90^\circ - 300^\circ$ CML when the spacecraft were in the northern hemisphere. The crossings of the magnetic equator by the spacecraft are indicated by two arrows.

After V2 encounter, the measured axial ratio of nKOM is very close to the ratio of circular polarization of the emission since the source direction was nearly perpendicular to the electric antenna plane. The axial ratio of one hundred events following the encounter was measured. The mean value and standard deviation are shown in Figure 4. The general behavior of the axial ratio in terms of longitude is sinusoidal, in phase with the spacecraft magnetic latitude (also plotted in Figure 4). On the same figure are represented the two CML values where the occurrence probabilities for the two circular polarizations RH and LH become equal. These values fit well the axial ratio plot. The important result is, that for high magnetic latitude, the axial ratio saturates at about 0.6.

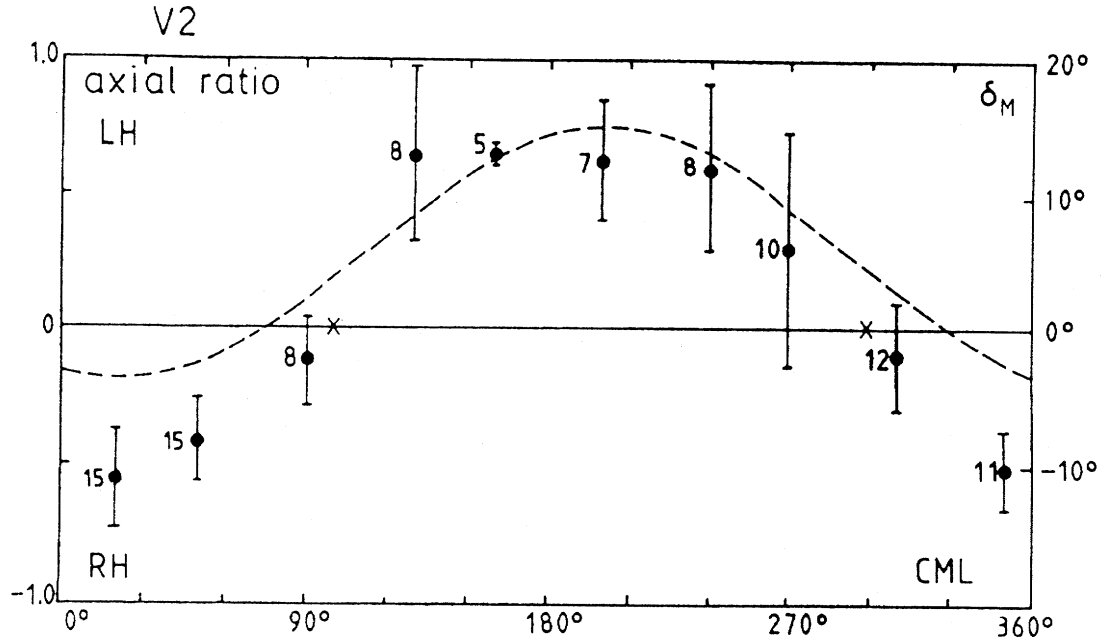


Fig. 4: Measured axial ratio of nKOM (left scale) at different longitudes. Mean values, standard deviations and the number of events are indicated. The two crosses show the CML values where the occurrence probabilities for RH and LH emissions become equal. The dashed line shows the magnetic latitude of spacecraft (right scale).

1.5 Power spectrum

Desch and Kaiser (1980) showed that the bKOM density spectrum decreases gradually in intensity with increasing frequency. On the other hand they reported that the bKOM component is more intense by a factor of 2 or 3 when seen from the dayside hemisphere. But the comparison was only made for V2 pre- and post-encounter observations and not for V1 pre- and post- encounter observations. Since the intensity might also depend on the spacecraft declination, the variation in intensity with the observer's local time is not yet established. The average flux density spectrum of nKOM has not yet been determined; only the flux density of two events was reported by Kaiser and Desch (1980). The drop in intensity at increasing frequencies is very large, more than 100 dB per decade.

1.6 Frequency range

Leblanc and Daigne (1985b, Figure 8) displayed histograms showing the percentage of rotations when bKOM emission occurs at a given frequency. From the PRA records the low frequency cut-off of bKOM is about 39 kHz and only a few events were observed down to 20 kHz. The highest frequency limit was typically less than 500 kHz, except for one month before V2 encounter when the frequency limit reached more than 1 MHz. These figures show that the highest frequencies of bKOM are better observed on the dayside hemisphere, and mainly for an observer at high latitude. On the other hand the low frequency limit of bKOM is highly fluctuating (developed in Section 3.1). The frequency range of nKOM is much smaller, usually from 40 kHz to 150 kHz. However,

large fluctuations can be observed, the lowest frequency limit being about 20 kHz and the highest frequency being ~ 250 kHz.

1.7 Rotation period

The plot of occurrence of bKOM as a function of System III longitude clearly shows (Desch and Kaiser, 1980; Leblanc and Daigne, 1985b) that the rotation period of bKOM is well represented by System III. On the other hand, the plot of occurrence of nKOM shows during some periods a drift towards higher longitudes (Kaiser and Desch, 1980; Daigne and Leblanc, 1986).

Kaiser and Desch (1980) have considered that one or two emission sources were drifting for about 50 Jovian rotations. They obtained a rotation lag of 3–5%. Even if the emission was not observed for some rotations, it appeared to resume at the coherent phase and Kaiser and Desch concluded that they represent long-lived source regions.

In order to measure the rotation period of the nKOM sources and its possible frequency dependence, Daigne and Leblanc (1986) have considered each individual event and its occurrence at the next rotation. From one rotation to the next, the frequency range of occurrence may differ, but there is no definite trend to lower or higher frequencies. The time delay between the two emissions has been measured by fitting the time profiles observed at the same frequency. Due to the numerous data gaps, only 35 events for V1 and 25 events for V2 could be measured. The results are shown in Figure 5. The rotation period of nKOM is longer than the System III Jovian rotation period, the average values of the corotation lag for each observed frequency are in the range 2–5%. It cannot be clearly established that the rotation period increases with decreasing frequency although there is such a trend. The rms deviation ($\sim 2.5\%$) reflects rather the *observed fluctuations* in rotation lag than random errors in measurements.

The life-time of a nKOM source is crucial for the understanding of this emission. Two time scales must be considered: a few Jovian rotations when the emission is successively observed, and a few hundred of Jovian rotations when a kind of organization in the occurrence diagram is observed. In Figure 6 are plotted the occurrence of nKOM events in terms of phase, or of CML for 200 rotations. The dominant feature in the organization of nKOM sources is a drift through a phase range of about 360° followed by a *stable phase*, each sequence lasting for about 30 rotations. This organization is better seen when applying a rotation lag of 3%. A *wavy pattern* appears, which implies that the rotation period is not constant for the nKOM source regions and may change rather abruptly. We point out that the same pattern was observed simultaneously by V1 (post-encounter) and V2 (pre-encounter) during a common period of observations. This pattern exhibits a rotation lag of 2.6% from rotation 2060 to 2100 and then a corotation until rotation 2130 (Daigne and Leblanc, 1986).

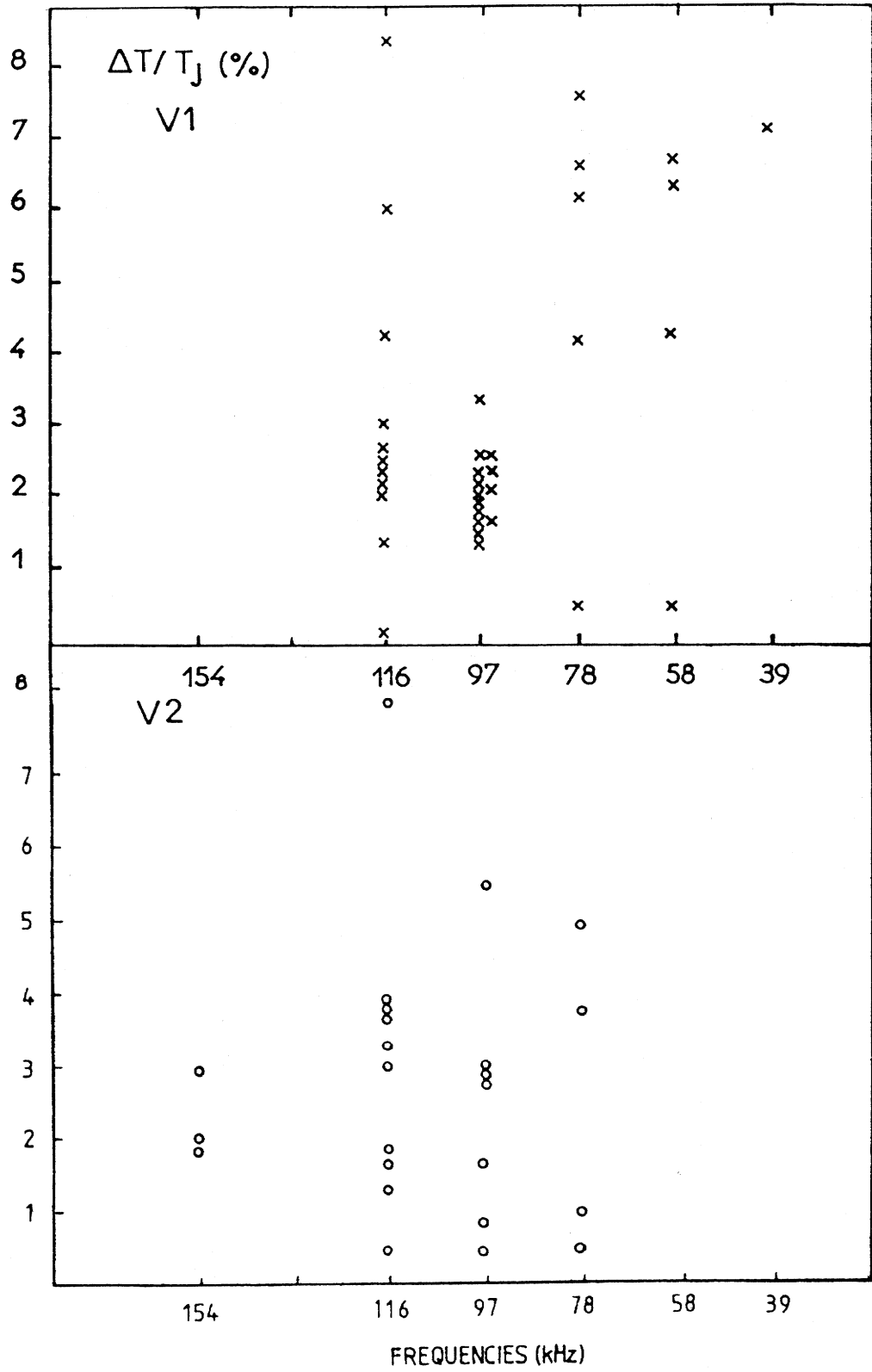


Fig. 5: Individual measurements of corotation lags of nKOM events in terms of frequency for V1 and V2 observations.

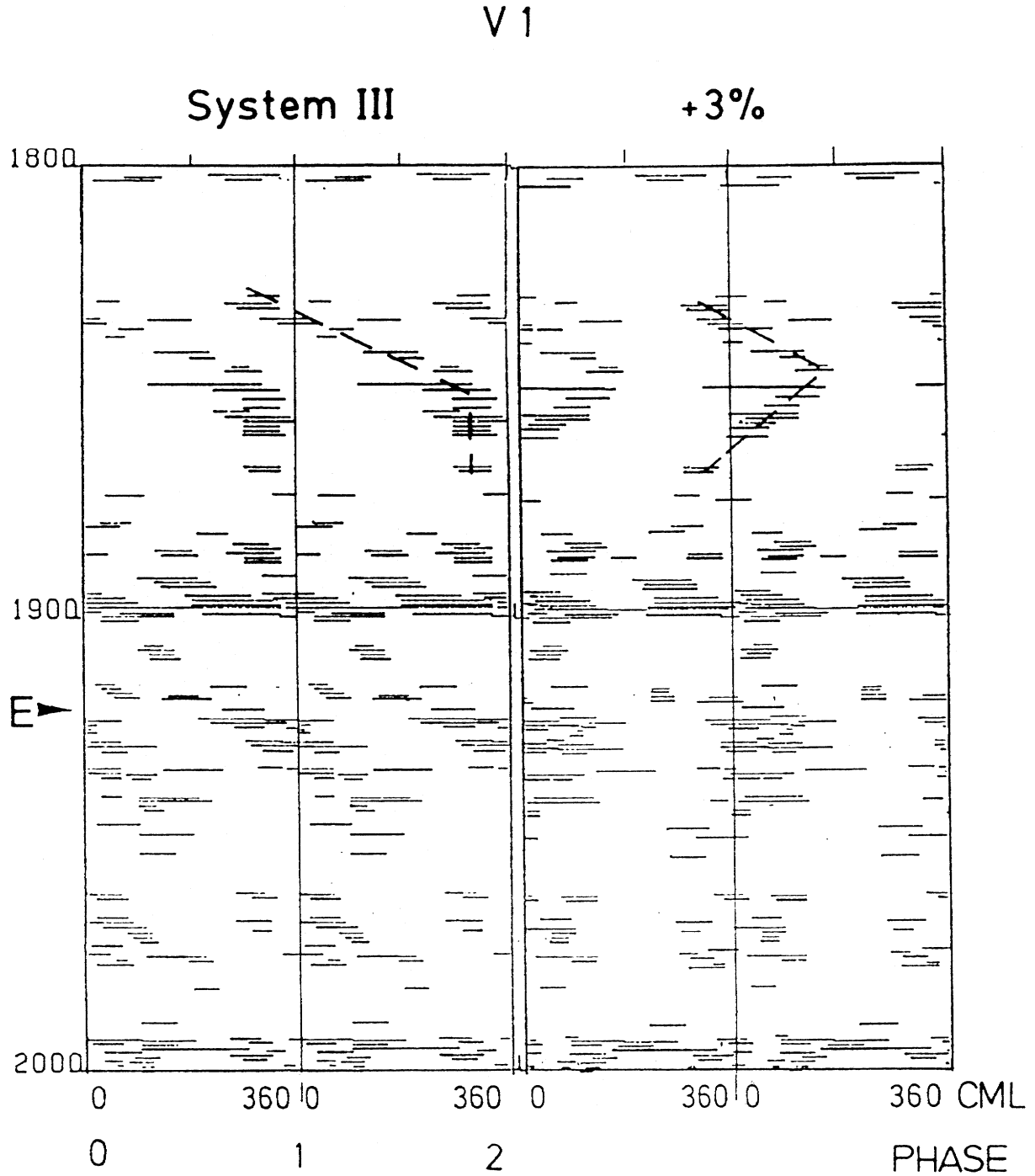


Fig. 6: Occurrence of nKOM events in terms of phase and CML in reference System III and with a + 3% corotation lag, the origin being rotation, 1800. The plots are repeated for phases from 1.0 to 2.0. The arrow indicates the encounter for V1. The most typical organization of nKOM is shown by a dashed line: a sequence with a corotation lag followed by a sequence of corotation.

The long term organization of nKOM is further studied through the method of period finding and the estimator given by Bopp et al. (1970). For a trial period, the occurrence of nKOM events was determined in terms of phase (Figure 7) for some peculiar values of the lag. For V1 observations, the best fit is obtained for a rotation lag of 3%. For V2 observations, the estimator shows several dips, which means that the long-term organization of nKOM events is still less clear than for V1 observations. The wavy pattern already noticed in Figure 6 is indicative of a phase modulation of the main periodicity; it could produce the multiple dips observed in the fit estimator.

Complementary information is given by the amplitude of the main peak of the occurrence, and its variation in terms of the period, as shown in Figure 7d. For V1 observations, two narrow peaks are revealed at 0.0% and 3.0% corotating lag. As for V2 observations, the dominant peak is observed at 0.0%, and a secondary peak at 2.7% corotating lag. These plots also show larger fluctuations for V2 than for V1 observations.

Two different methods were used to study the rotation of nKOM. The superposition of profiles, from one rotation to the next at the same radio frequency, gives corotation lags in the range 0–8%; the average value is, respectively 3.2% and 2.7% for V1 and V2 observations. The method of period finding, or superposed epochs, shows that *two* rotation periods clearly appear in the nKOM occurrence, one at System III, and the other at System III + $\sim 3\%$. The two methods are complementary and may not give exactly the same result. Indeed, the first applies to short time scales, or within the lifetime of a source region. The second one is global and applies whatever the time interval between events; therefore its results refer mainly to the long term occurrence of the source regions.

It is interesting to note that after Kaiser and Desch finding the nKOM rotation period rotating at System III + 3%, many authors discovered that the brightness in the Io torus rotates at this new rotation period (Trafton, 1980; Pilcher and Morgan, 1980; Trauger et al., 1980; Roesler et al., 1984). However, Sandel (1983) noted also the presence of a System III periodicity, and Pilcher and Morgan (1985), and Pilcher et al. (1985) present observations requiring two separate plasma sources, one rotating with System III and the other rotating at a slower rate.

In a recent paper, Sandel and Dessler (1988) have considered the rotation period of the brightness of the Io torus from V2 ultraviolet spectrometer and ground-based observations. They found, from V2 observations, evidence for modulation of the brightness of the approaching ansa at the System III period. Periodograms show two peaks of the approaching ansa, one at System III ($1.000 P_{III}$) and the other at System III + 3% (System IV). At the receding ansa, there is only one peak at System IV (Figure 8). When selecting those EUV observations within 3.5 days of the times of alignment of the probability peaks in System III and System IV, Sandel and Dessler found that the modulation of the EUV is enhanced at these times.

Sandel and Dessler have also used nKOM catalogs of Kaiser and Desch (V2 observations) and of Daigne and Leblanc (V1 observations) to look for periodicities in the occurrence of nKOM. Using a technique (superposed epoch analysis) similar to that used by Daigne and Leblanc, they confirmed their results, i.e. two periods, one at System III and the other at System IV, modulate nKOM occurrence. When selecting nKOM episodes within one day

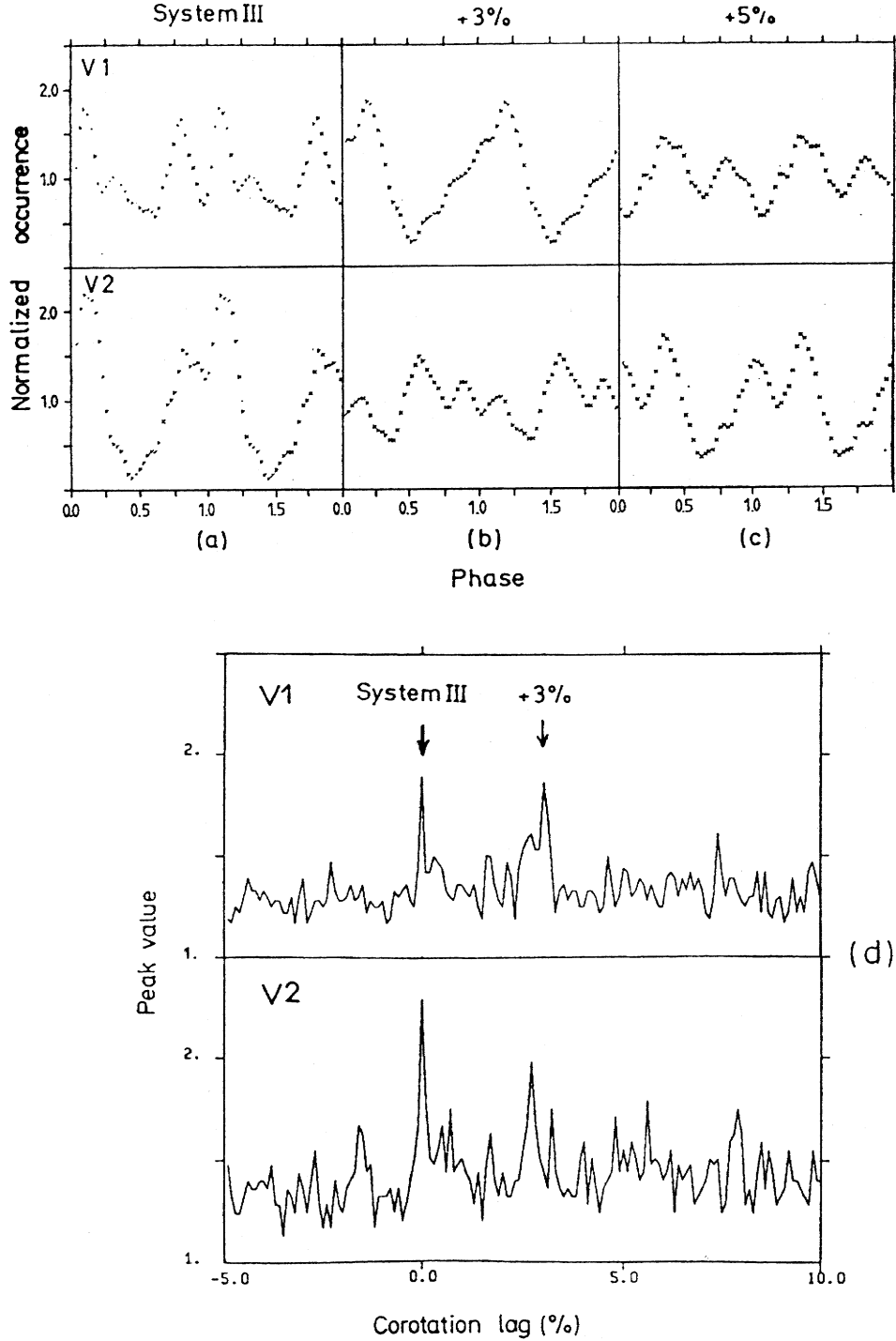


Fig. 7: Normalized occurrence of nKOM events plotted versus phase: a) in reference System III, b) with + 3% corotation lag, c) with + 5% corotation lag. The observing periods are rotation 1820 – 2150 for V1 and rotation 2050 – 2300 for V2. The plots are repeated for phases from 1.0 to 2.0. Well defined peaks appear. d) Amplitude of the main peak of the occurrence versus the corotation lag of the reference system. nKOM events exhibit corotation lags (+ 3% for V1 and + 2.7% for V2) and corotation for both spacecraft observations.

of alignment and anti-alignment, they showed that the probability of detecting nKOM is strongly dependent on alignment (Figure 9a), and therefore exhibits a period of ~ 14 days or ~ 33 Jovian rotations. This period duration is very close to that found by Daigne and Leblanc (~ 30 Jovian rotations) in the organization of nKOM sources (Figure 6). Sandel and Dessler propose a tentative explanation of this property of the Jovian magnetosphere in terms of a modulation of corotating convection as originally suggested by Vasyliunas (1978, 1983). The System III longitude from which the convection is organized is called the active sector (longitude range $\lambda_{III} = 150^\circ - 320^\circ$) which contains nearly all the Jovian magnetospheric phenomena. There would be another active sector to account for the System IV longitudinal asymmetries, which would dominate in the outer part of the torus. It is then expected a modulation of the strength of the corotating convection pattern at a period of about 14 days.

1.8 Discussion

The two types of Jovian kilometric radiation, bKOM and nKOM, have been distinguished by their different signatures in the dynamic spectra (Kaiser and Desch, 1980): nKOM is a smooth emission with a narrow bandwidth, conversely, bKOM is a spiky emission with a broad bandwidth. From the extensive studies of nKOM and of bKOM, the similarities and differences between these two types of emission are now updated.

Two *similarities* can be pointed out:

- polarization reversals from one magnetic hemisphere to the other,
- no local effects, from dayside to nightside observations, on the sense of circular polarization, and on the local occurrence probability.

But the two emissions are *different* in many ways:

- the senses of circular polarization are opposite for the same CML range,
- the occurrence probability in CML is much greater for bKOM than for nKOM. For bKOM the maximum reached 80% before encounter, whereas it does not exceeds 26% for nKOM,
- the rotation period of nKOM source regions shows long term fluctuations, sequences with corotation lags in the range 3–5% and sequences of corotation with System III.

These differences clearly justify the first identification of the two types of emission and imply that the source regions are distinct. The beaming, the emission mode, the radiation mechanism and the triggering source have also to be considered separately.

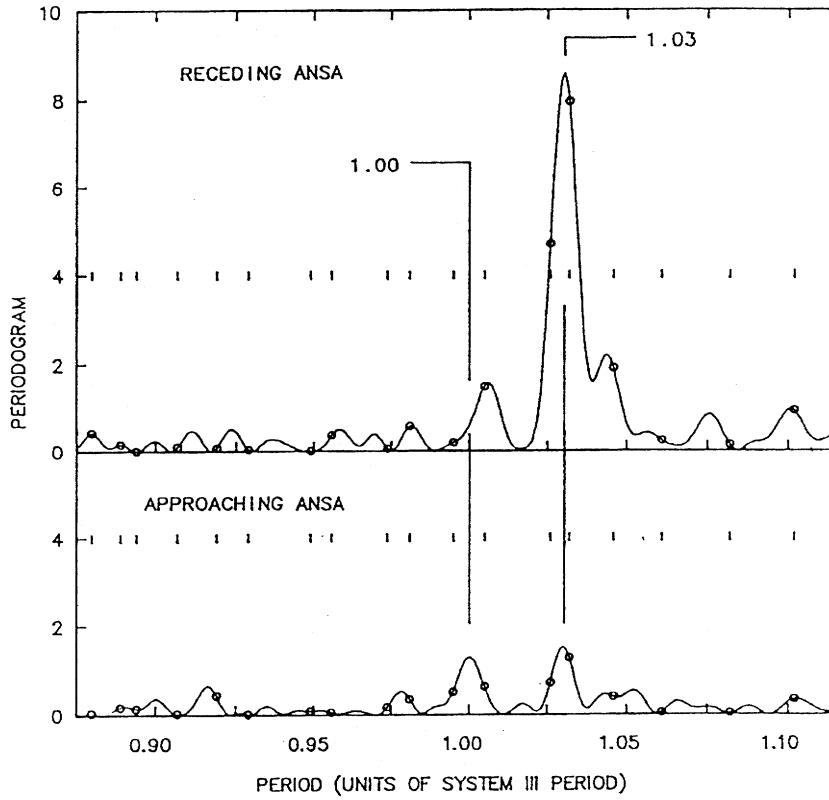


Fig. 8: Periodograms for approaching and receding ansas of the plasma torus (EUV observations). Significant modulation at System IV (1.03) is present in both ansas, and the brightness of the approaching ansa is modulated at System III (1.0) as well (after Sandel and Dessler, 1988).

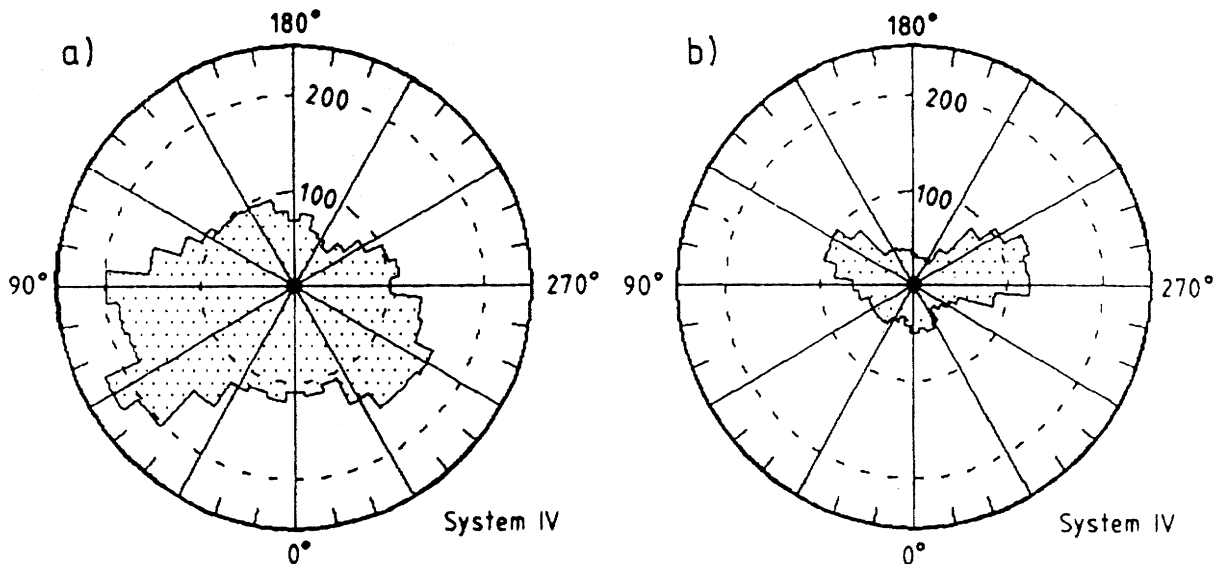


Fig. 9: Relative probability of observing nKOM as a function of the System IV. The observations have been divided into two partitions, (a) two-day period about alignment, and (b) two day-period about anti-alignment of the peaks in System III and IV. Detection of nKOM is more likely during times of alignment (after Sandel and Dessler, 1988).

2. Inferred properties: beaming, emission mode, and source location

2.1 Beaming in magnetic latitude

During dayside observations the excursion of the spacecraft in magnetic latitude was -8° to $+14^\circ$ (V1) and -3.5° to 18.5° (V2). We were then able to determine the beam width at least in the northern hemisphere. For bKOM, the position of the maximum of the main component at CML $\simeq 200^\circ$ corresponds to the maximum in magnetic latitude of the observers. At low magnetic latitude neither source is observed. The difference in the occurrence probability for each spacecraft observations is explained by the higher magnetic latitude reached by V2: the observer is swept by the northern emission beam for a longer period of time for each Jovian rotation. As a result the occurrence probability of bKOM is greater and the half-height width of the peak is larger for V2 than for V1 observations (Figure 2a). These two different widths are consistent with a low boundary of the northern emission beam of about 11° at 78 kHz, in agreement with Kurth et al. (1980b) who found 10° at 56 kHz.

On the night side the magnetic latitude excursion of both spacecraft was -6° to 16° . The occurrence diagrams of bKOM show two peaks in CML, one at 140° and a broader one at about 260° , at symmetric longitudes with respect to 200° CML (Figure 3a): If we consider that the observer is swept by the beam twice during a single Jovian rotation, two peaks in the occurrence diagrams must be observed. From the widths and peak positions in the occurrence diagrams we are able to deduce the beam boundaries at a given frequency; at 78 kHz the northern beam boundaries are 11° and 14° in magnetic latitude.

For nKOM, only the observations on the nightside were considered. The peak in occurrence probability occurs at a magnetic latitude $\delta_M \sim 7^\circ$ for V1 observations and at $\delta_M \sim 10^\circ$ for V2 observations. The deduced boundaries of the emission beam in the northern hemisphere are 2° and 12° . The depletion in the occurrence diagram in the range 160° – 240° CML cannot be due to a masking effect by bKOM since its occurrence is weaker in the range of 200° CML after encounters. When comparing bKOM and nKOM, we notice that:

- the nKOM occurrence shows a slight depletion in the vicinity of the magnetic equator but not the wide shadow zone observed for bKOM,
- the axial beaming in magnetic latitude measured for the northern hemisphere is closer to the equator for nKOM ($\delta_M \simeq 7^\circ$) than for bKOM ($\delta_M \simeq 13^\circ$) at 78 kHz.

2.2 Emission mode, radiation mechanism and source location

One principal result on the bKOM is that the emission consists of two *components* polarized in the opposite sense. The northern component observed regularly at most of Jovian rotations is right-hand polarized and the southern component observed only from time to time is left-hand polarized. There is no polarization reversal from day- to night-time observations. The second result is, that the peak of occurrence probability does depend on the observer's local time: for dayside observations it occurred at 200° CML, and for

nightside observations two peaks occurred at 150° and 300° CML. The results on the beaming, polarization and occurrence probability led Leblanc and Daigne (1985a,b) to conclude that bKOM source must be located at the Io torus, at all longitudes of the planet. Moreover, they showed why the hypothesis of a source at the polar region (Green and Gurnett, 1980), or fixed on the dayside of the planet (Kaiser and Desch, 1980) were not in agreement with the deduced polarization, and consequently, why it must be ruled out.

For nKOM, the emission is left-hand polarized when seen from the northern hemisphere, and right-handed when seen from the southern hemisphere. There have been many suggestions that nKOM derives from the Io plasma torus (Warwick et al., 1979a; Kaiser and Desch, 1980; Jones, 1980), and from polarization measurements it has been suggested that the emission is in the O – mode.

Several emission mechanisms have been proposed for the Terrestrial Myriametric Radiation (*TMR*) and we shall see which ones are consistent with KOM emission. Melrose (1981) reviewed the non-thermal radio emissions generated from electrostatic noise near the upper hybrid frequency. When applied to the terrestrial continuum the most favorable mechanism for the conversion into the O – mode appears to be the coalescence with a low frequency wave (ion-cyclotron waves). Due to the strong analogy between terrestrial escaping continuum radiation and nKOM (Kurth et al., 1980b), this latter mechanism should be considered for nKOM. Although the efficiency of such an interaction would be adequate, Barbosa (1982) pointed out that there is no observational evidence for the coexistence of the two wave types.

Jones (1980) proposed that Jovian kilometric radiation was produced by mode conversion, via a radio window, of electrostatic upper hybrid waves to *O – mode* electromagnetic radiation, in the density gradients at the Io torus. The theory predicts the emission at the plasma frequency. This radiation mechanism has been successfully applied to bKOM (Jones, 1986a; Jones and Leblanc, 1987) and to nKOM (Jones, 1987b), and will be developed by Jones in these proceedings. The main result of this approach is that the beaming is inherent to the conversion mechanism and depends on the characteristic frequencies of the source plasma. As a consequence, the beaming angle to magnetic equatorial plane increases with increasing frequency in the bKOM source region and by remote sensing technique the plasma torus density profiles can be determined. That theory applied to bKOM leads to a source location at $\pm 2^\circ$ from the magnetic equator, the northern beam emerging from a source at negative magnetic latitude and the southern beam from a source at positive one. The nKOM emission would also be produced at the Io torus, but at latitudes $\geq 8^\circ$ (Figure 10).

More recently, Fung and Papadopoulos (1987) proposed that upconversion of two hybrid branch electrostatic waves can produce electromagnetic radiation that can account for the nKOM emission. The emission mode would be at twice the upper hybrid frequency: that theory was developed by Roux and Pellat (1979) who showed that the non-linear beating is efficient in regions where $f_p \leq f_c$. The condition $f_p \leq f_c$ is fulfilled at the inner part of the Io torus and along its boundary where f_{UH} varies from 200 kHz at $4.5 R_J$ down to 50 kHz at $6.5 R_J$. Therefore the emitted frequencies in these regions would be 400 to 100

kHz. This theory predicts also that the emission is beamed at large angles with respect to the background magnetic field.

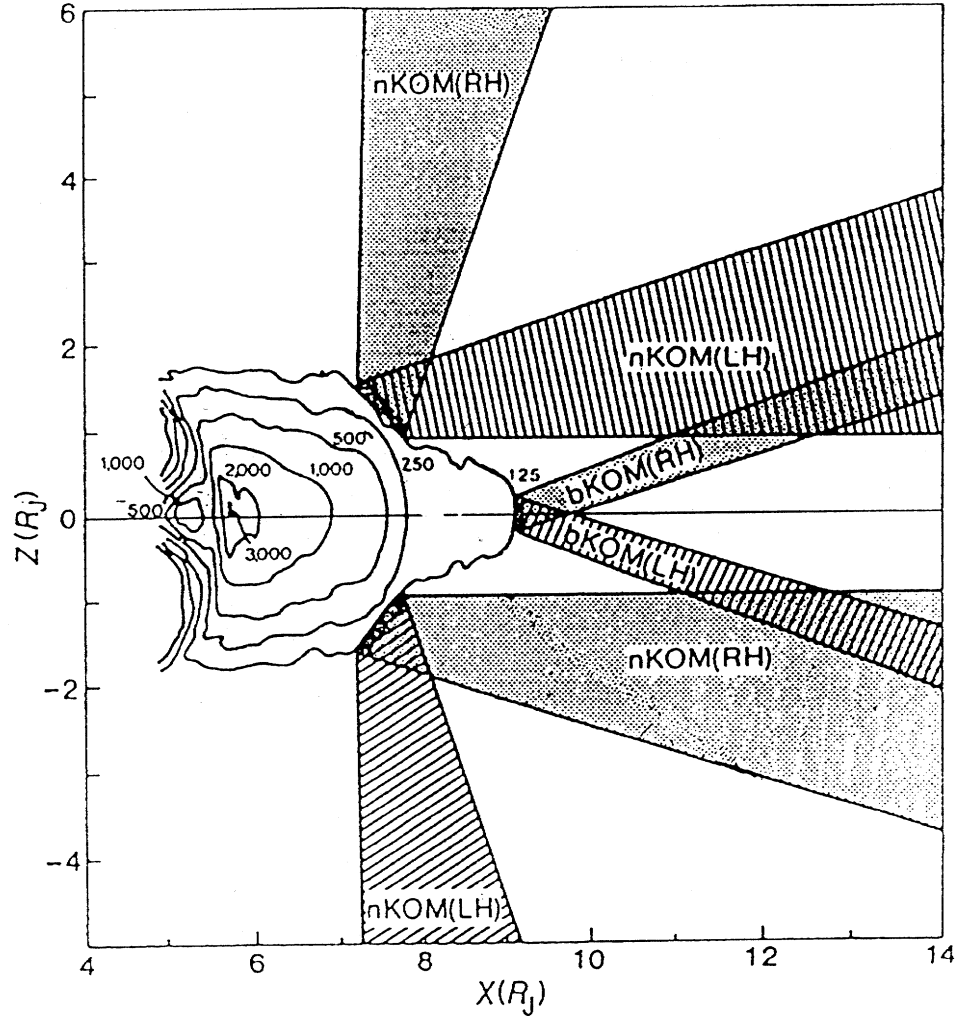


Fig. 10: Picture showing $nKOM$ and $bKOM$ 100 kHz sources (Jones, 1987b). The various beams are sketched and their polarizations indicated.

3. Io torus variability

In the last section it has been established that $bKOM$ and $nKOM$ sources are likely located at the Io torus, the first one at the magnetic equator, and the second one at higher latitudes of the torus. From the characteristics of the source plasma depends the beaming of the emission. Therefore it is expected that temporal fluctuations in the Io torus will produce fluctuations in the beaming. This is now developed in the following.

3.1 Variability of the beaming

For bKOM emission it has been noticed that the duration and the emitted frequencies of an event vary from one rotation to another. In general, when the duration of an event is a few hours (or $\sim 150^\circ$ in longitude), it is observed within a large frequency range as if the boundaries of the beam came closer to the magnetic equator, so that a fixed observer (V1 or V2) will be swept by the entire source beam. On the other hand, during some periods, bKOM was not observed as if the beam went away from the spacecraft observing direction.

To test that point, we have compared the low frequency limit (LFL) of the bKOM emissions observed *simultaneously* by V1 and V2, when the two spacecraft were at the same zenographic latitude. Figure 11 shows that, indeed, the emission was not observed by both spacecraft during some periods, or that the LFL might occur only at frequencies higher than 170 kHz, instead of 20 or 40 kHz. Since we know that the occurrence probability is close to 80% at CML $\sim 200^\circ$, the absence of emission at that longitude must be interpreted as a change of the physical environment of the source region.

Since the magnetic latitude excursion of the spacecraft in the southern magnetic hemisphere was within -8° , the southern beam of bKOM source was scarcely observed; this is interpreted by the fact that the spacecraft were not usually swept by the southern beam, except when this latter comes closer to the magnetic equator. Indeed, before encounter, the southern beam was less often observed by V2 whose southern magnetic latitude was $\delta_M = -4^\circ$ than by V1 ($\delta_M = -8^\circ$). After encounters, both spacecraft were at the same zenographic latitude (5°) and the southern beam was observed with the same occurrence by both spacecraft. In particular, during simultaneous observations when the southern beam was observed by V1, it was also observed by V2.

The comparison of dayside and nightside observations of bKOM led Leblanc and Daigne to infer that the beaming of bKOM changes with local time. In particular, it would be much narrower on the nightside than on the dayside (Figures 2 and 3). This must be the consequence of an asymmetry in the density profile of the Io torus between dayside and nightside.

For nKOM, the occurrence probability is peaked at 40° CML (System III); its value (about 25%) is much lower than bKOM value at its peak (85% at 200° CML). Daigne and Leblanc (1986) have shown that the nKOM peak is due to the southern beam emission. It is not yet well understood why the southern beam is more often observed than the northern one, and this cannot be due to the spacecraft magnetic latitude excursion which was higher in the northern than in the southern magnetic hemisphere. One explanation could be that there is an asymmetry in the Io torus with respect to the centrifugal equatorial plane.

On the other hand, to explain the frequent disappearance of nKOM, Jones (1987b) proposed that if the total bandwidth of nKOM were larger than f_c , nKOM would consist of one or more narrow band emissions corresponding to the upper hybrid frequency $f_{UH} \approx (n + 1/2)f_c$, which results in a spacing of ~ 20 kHz. Since the PRA receiver consists of a number of 1 kHz bandwidth filters spaced 19.2 kHz apart, any fine structure in nKOM with a 20 kHz spacing would not have been resolved, and no signal would have

LOW FREQUENCY LIMIT OF bKOM

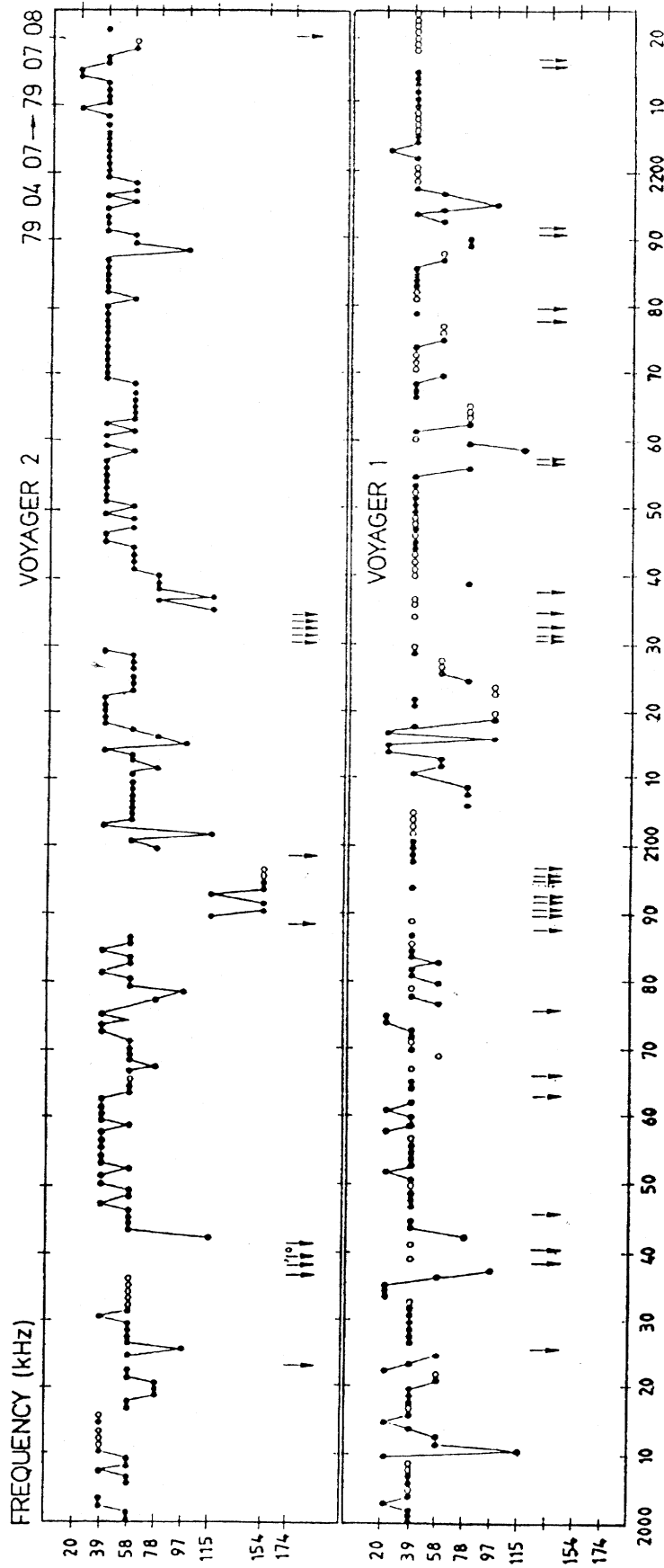


Fig. 11: Low frequency limit of bKOM observed simultaneously by V1 and V2. The measured points are full circles. The empty circles are inferred values. The arrows indicate that the low frequency limit is higher than 174 kHz.

been recorded in any of the PRA receiver channels if the banded nKOM were at frequencies between filters. Another interpretation of the disappearance of nKOM is based upon the beaming angle: the orientation of the density gradient with respect to the magnetic field determines the source location and the beaming angles of the resultant radiation. A slow time variation of the density gradient would lead to large time variations of the beaming angles and to temporary disappearance of nKOM.

For these two interpretations the comparison of nKOM occurrence for simultaneous observations and for the same observing geometry would be very important.

3.2 *Io torus density profiles*

One consequence of Jones' theory (1986a) is that a remote sensing technique could be used to determine the torus characteristics when the beaming of bKOM is known. In that theory, it is predicted that the emission is at the plasma frequency and the beam angle with the magnetic equatorial plane is defined by

$$\alpha = \arctan(f_c/f_p)^{1/2}$$

The source is assumed to be located within $\pm 2^\circ$ from the magnetic equator. Therefore the knowledge of start and end times of bKOM at different frequencies, and of the spacecraft magnetic latitude, led Jones (1986a) and Jones and Leblanc (1987) to determine the plasma density profiles of the Io torus. This has been done for bKOM observed during 9 Jovian rotations when V2 was close to Jupiter encounter. Some other density profiles seen in Figure 12 were obtained when V2 was in a larger distance range (323 to 223 R_J) (These profiles were kindly provided by D. Jones, private communication). They are remarkably consistent, with similar gradients, and in very good agreement with the in-situ measurements of the Io torus density by V1. As a consequence, the remote sensing technique could be a powerful method of determining the torus characteristics when no in-situ measurements are available.

3.3 *Solar wind control of bKOM*

The bKOM has been investigated for possible solar activity influence by Barrow et al. (1988). Set against a background of correlation for the Jovian DAM and HOM as well as for the Saturnian SKR and the terrestrial AKR it might seem remarkable if no correlation effects should be found in the present case. It must be remembered, however, that the terrestrial, the Saturnian and the Jovian DAM and HOM radio sources are all believed to be located within the auroral regions which are more responsive to solar wind fluctuations. No solar wind control has been found for terrestrial myriametric radiation (TMR), the source of which is usually located at the plasmopause or the magnetopause, and which might be regarded as the terrestrial counterpart of Jovian kilometric radiation. As proposed by Jones (1980), Leblanc and Daigne (1985a,b) and Jones and Leblanc (1987), there are arguments for locating the bKOM source at the Io torus, and any possible solar wind effect must be compared to that exerted on the terrestrial plasmasphere when it is compressed during periods of increasing magnetic activity (Gurnett and Frank, 1976).

Only Voyager 2 data (1979) show correlation effects and then only when *lower frequency* bKOM events, or *lower average energies* per rotation, are selected for epochs. Energy

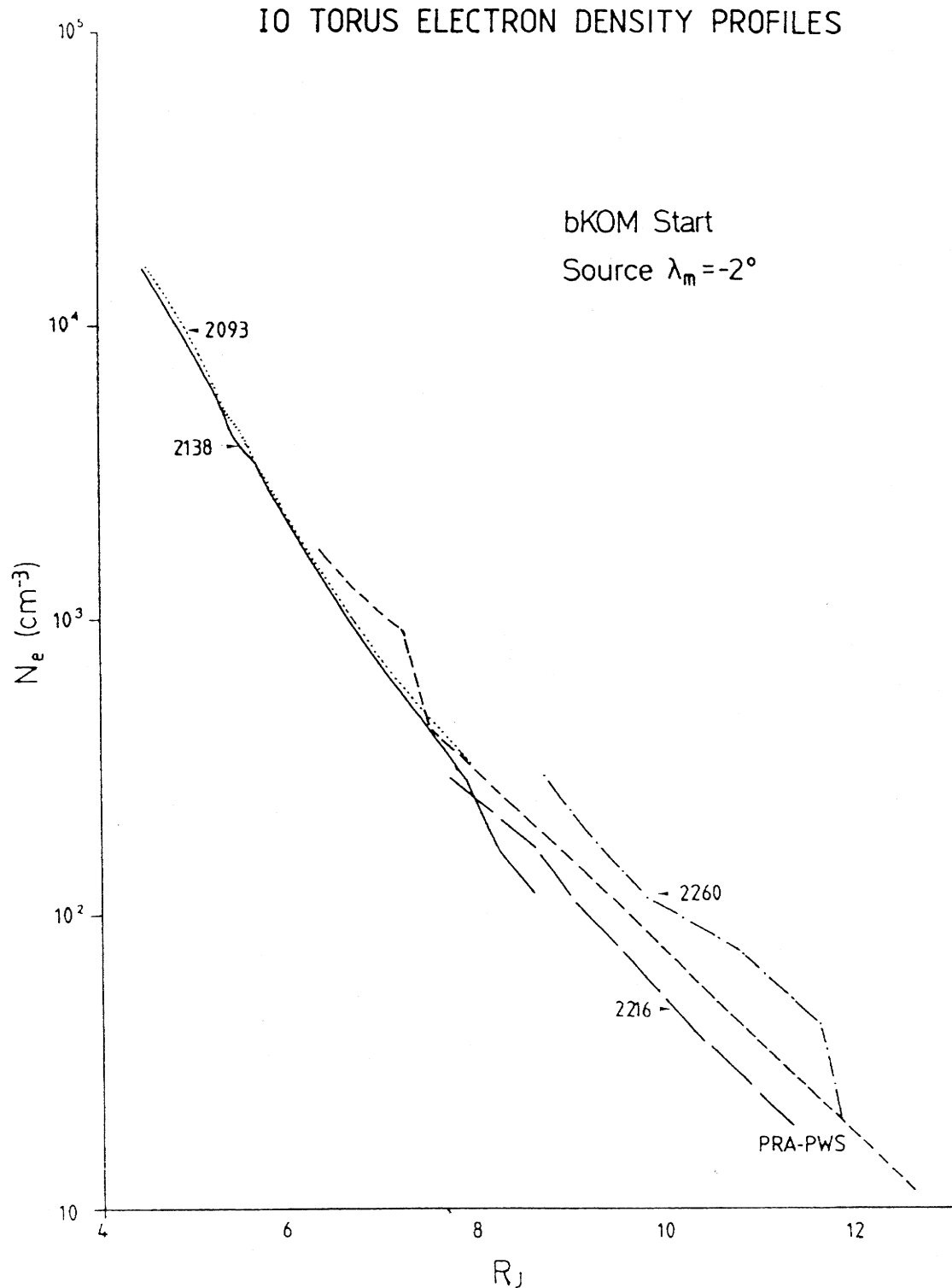


Fig. 12: Plasma density profiles of the Io torus obtained by remote-sensing technique using the start times of bKOM when V2 was inbound from 323 R_J to 223 R_J . (These profiles were kindly provided by D. Jones, private communication.) For comparison, profiles obtained from in-situ measurements by V1 by the plasma density PRA experiment (Warwick et al., 1979a) (dashed line).

correlation is then significant throughout the entire period DOY 20 to 180 while event correlation is significant only during the period DOY 120 through 180, when the interplanetary magnetic field (IMF) sector structure was well-defined. In these cases, correlation is highly significant ($\sigma' > 4.0$) for the solar wind density and pressure and for the IMF magnitude. The details of that study are given by Barrow in these proceedings. The main result is that when the sector structure is well-defined, lower-frequency bKOM events occur after a sector boundary has passed Jupiter, a day or two before the sector centre arrives, as the solar wind density and the IMF magnitude are approaching their maximum values. The density of the emission may be lower a day or two after this, as the density and the IMF magnitude pass their maximum values (Figure 13).

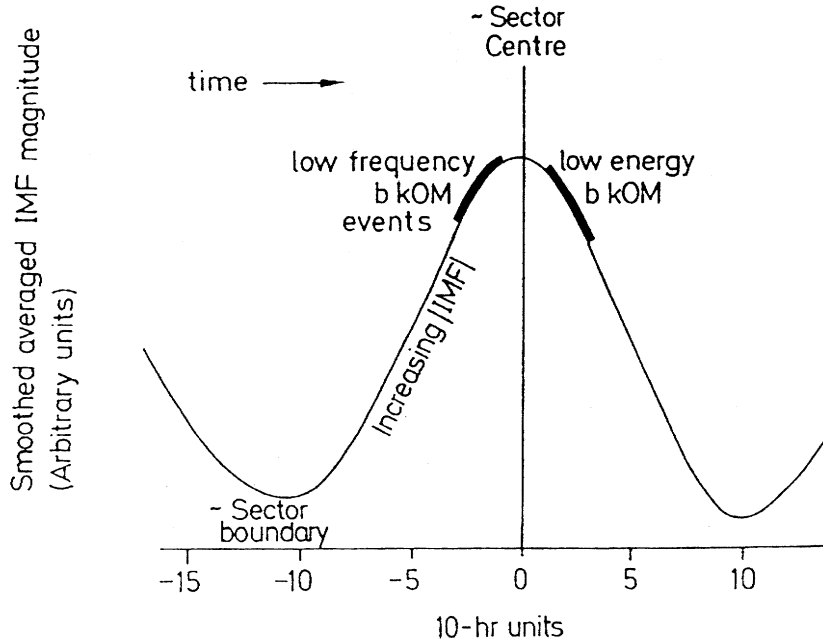


Fig. 13: General picture of solar activity influence on the bKOM represented by the progress of a sector across Jupiter (Barrow et al., 1988).

The absence of correlation, when higher frequency or higher average energies events are included in the analyses, is not yet well understood. The control of the solar wind on the lower emission frequencies and the lower average energies may be due to variations in plasma density in the outer Io torus which would be more susceptible to external influence than the inner torus. Gurnett and Frank (1976) have found that weak continuum terrestrial radiation is correlated with magnetic activity. If the outer Io torus is compressed in the same manner as the terrestrial plasmasphere during increased magnetic activity, this could increase the density gradient. According to Jones (1986a), Budden and Jones (1986), an increase of the density gradient in the Io torus leads to more efficient conversion of electrostatic upper hybrid waves into the O – mode, thus increasing the probability of bKOM.

It is clear that lower-frequency/lower-energy correlation is not always present or that it is often obscured by some other stronger control. We suggest that this control is due

to changes in the isoionic contours of the Io torus which are conducive to variations in the beaming of the source which is located at the torus. Fluctuations of the Io torus parameters have been reported by Hill et al. (1983) and they may be dependent upon Io vulcanism.

Conclusion

The Jovian magnetosphere with its Io plasma torus is unique. The many studies of the Jovian kilometric radio emissions have led to the location of two distinct radio sources at the Io torus, one relative to bKOM and the other to nKOM. From the study of these radio sources, it has been possible to determine properties of the Io torus, in particular its temporal variability and its dayside – nightside asymmetry. With the analysis of nKOM occurrence, two rotation periods, one at System III and the other at System III + 3%, have been found to modulate the emission. When the two periods were in alignment (~ 14 days period), the occurrence probability is much increased; the consequences on the corotating convection pattern have been suggested by Sandel and Dessler (1988).

Radiation mechanisms are discussed and compared with the observations. Jones' theory which predicts an O – mode emission, and beaming inherent to the conversion mechanism, seems to be the best suited for bKOM and nKOM emissions.

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